Exploring calorimetry new dimensions: a novel approach to maximize the performances of space experiments for high-energy cosmic rays.

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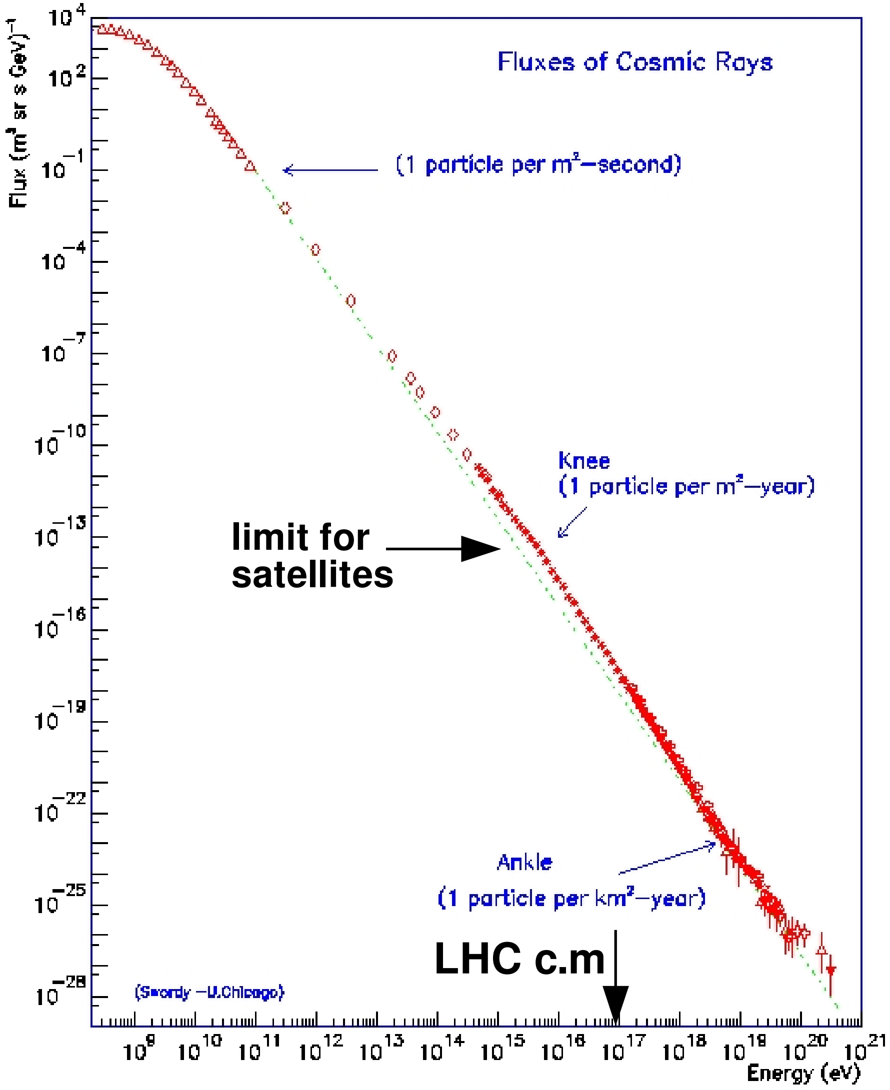
on behalf of CaloCube collaboration

The CaloCube Collaboration

- CaloCube is a three-years R&D project, approved and financed by INFN (Italy) in 2014, aiming to optimize the design of a space-born calorimeter for high energy cosmic rays measurements
- Participants:
  - INFN: Catania/Messina, Florence, Milano (Bicocca), Pisa, Pavia, Trieste
  - CNR-IMM Catania (dichroic filter deposition+ SiC photodiods)
  - IMCB-CNR Napoli (Surface treatments and WLS deposition)
  - Contacts with CNR Firenze
- In this presentation: scientific backgrounds (briefly), the CaloCube proposal, calorimeter performance (simulations and beam tests).

Cosmic Ray Spectrum



- From hundreds GeV up to 100 TeV is well approximated by a single power law ~ $E^{-2.7}$
- Structure around PeV, the Knee: energy limit of galactic accelerators?
- Very steep flux
- Large acceptance for high energy cosmic rays measurements is required
- Indirect measurements on earth: very large acceptance → high statistics → high energy
- Issue: affected by large systematic errors

Future satellite experiments

- Direct measurement: limit in energy due to small acceptance:
  - Nuclei below 100 TeV/n
  - Electron+positron below 1 TeV

Typical payload limitations:

- **Mass (~10^3 Kg)**
- **Power (~10^3 W)**
- **Down link capability (~10^2 Gb/day)**
- **Volumes (few m^3)**

Direct measurements of cosmic ray proton and nuclei spectra up to 1 PeV/n and electron spectrum above 1 TeV require:

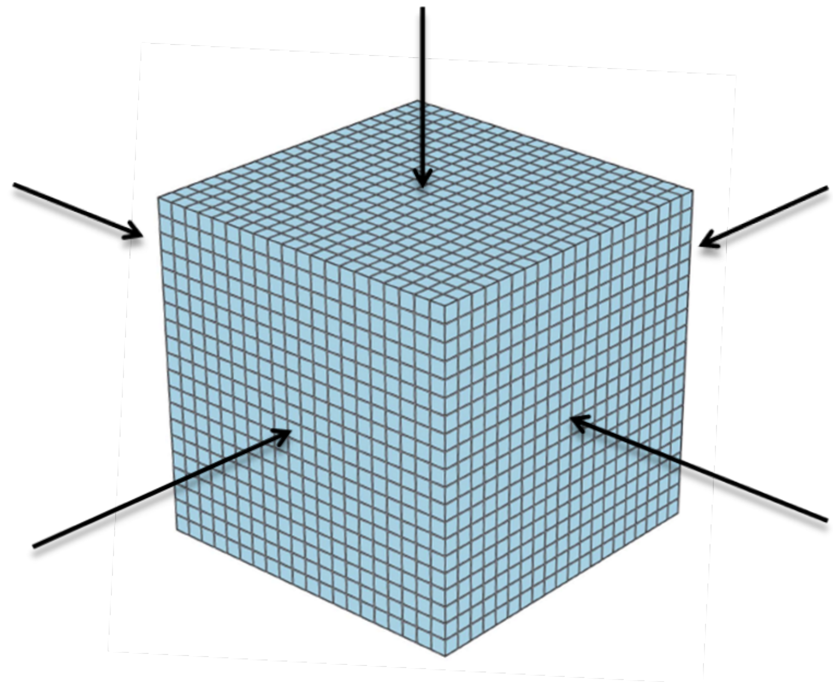
- Acceptance of few m^2sr
- Energy resolution better than 40% for nuclei and 2% for electrons.
- Good charge identification and electron proton rejection power (at least 10^5)
- High dynamic range

The Challenge

- **Deep homogeneous isotropic calorimeter:** accepts particles from all the directions
- **Large acceptance due to 5 faces detection,** mechanical supports and earth on bottom side
- **3D segmentation:** good e/p rejection, identification of shower axis and shower starting point

Calocube baseline design

- **20x20x20 cubic crystals CsI(Tl)**
- **Side = Moliere radius (3.6 cm)**
- **Double photodiode readout**
- **Double gain front-end electronics**



MonteCarlo simulations

- Based on FLUKA package
- 20x20x20 CsI(Tl) crystals, side ~ Moliere radius
- Support structures are in carbon fiber
- Gap between crystals: 0.3 cm
- Energy deposit in scintillating crystals are converted into photo-electrons using:
  - CsI(Tl) light yield (54000 ph/MeV)
  - light collection (~ Active area of PD / Area of one face)
  - quantum efficiency of PD @ 550 nm (emission peak of CsI(Tl))
- Energy deposit in PD due to ionization is taken into account

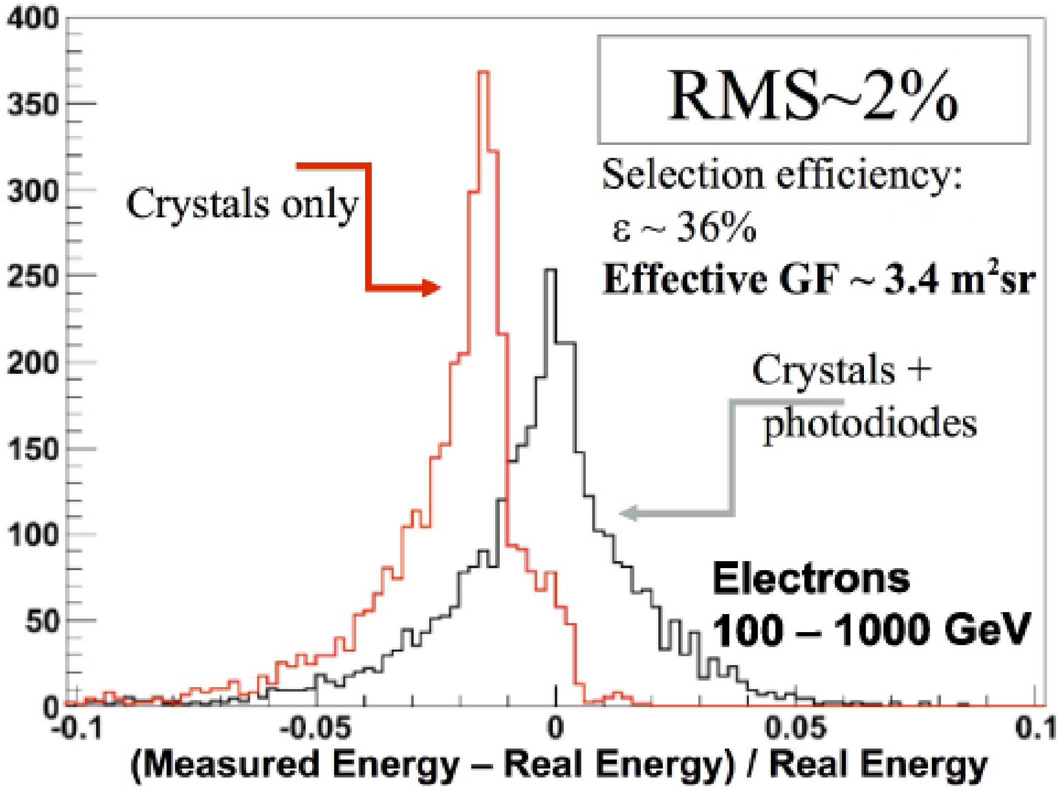
NxNxN	**20x20x20**
crystal side (cm)	3.6
crystal volume (cm^3)	46.7
gap (cm)	0.3
mass (kg)	1685
number of crystals	8000
size (m^3)	0.78x0.78x0.78
depth (R.L.) " (I.L.)	39x39x39 1.8x1.8x1.8
planar GF ($m^2 sr$) *	1.91

*** GF only for one surface**

- Protons and electrons simulated with an isotropic generation on the top surface of the calorimeter
- **GF of 5 faces = 9.55 m²sr**
- Effective geometric factor → $GF_{eff} = GF_{5faces} * \varepsilon_{selection}$

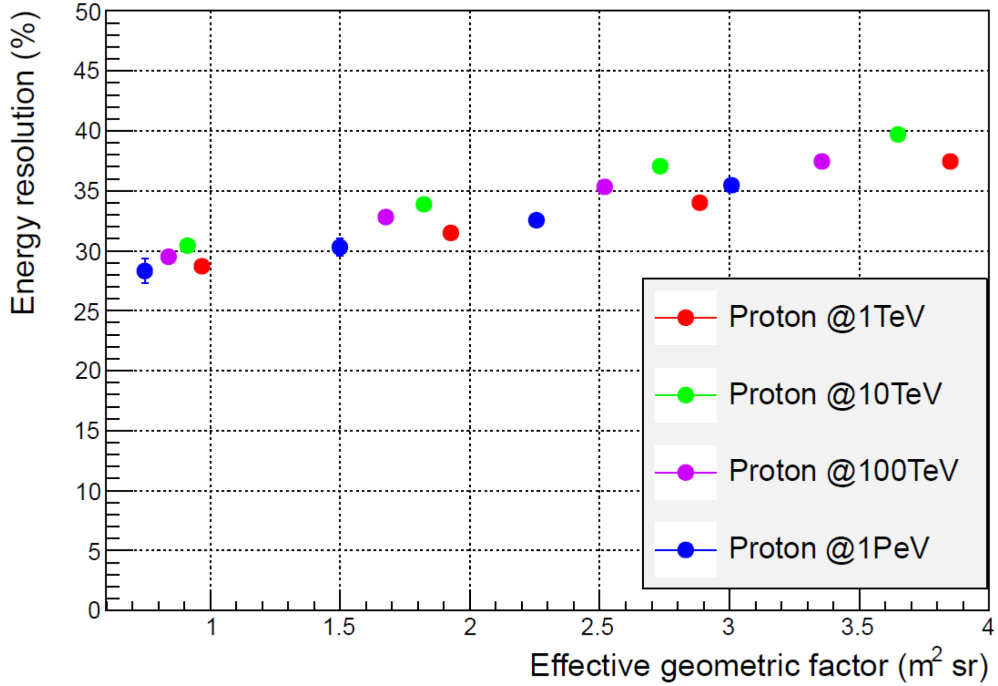
Electron energy resolution

- Isotropic flux of electrons from 100 GeV to 1 TeV
- Event selection: length of shower at least 22 X_0
  - Selection efficiency ~ 36%
  - Effective GF = 3.4 m^2sr
  - Energy resolution ~ 2 %
  - Direct ionization on PD ~ 1.7% of the mean signal
  - Low energy tails due to leakage and energy loss in passive materials (carbon fiber structures)



Proton energy resolution

- **Energy resolution for protons @ different energies as a function of the effective geometrical factor**



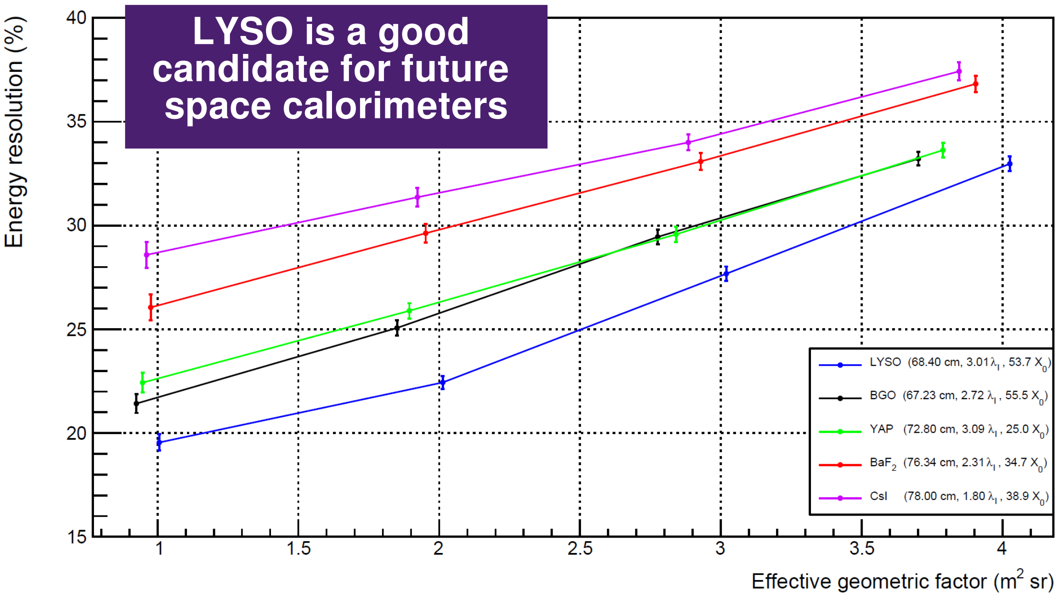
- **An increase in effective geometric factor (from ~ 0.8 m^{2}sr to ~ 3.5 m^{2}sr) translates in an increase of the energy resolution (from ~ 28% to ~37%)**
- **Energy resolution depends very weakly on the value of the primary particle energy up to PeV region**

Geometry & Materials

- **Optimization of energy resolution and acceptance for protons**
- **Same simulations and analysis with different materials and distance among crystals (gap)**

	CsI:Tl	BaF_2	YAP:Yb	BGO	LYSO:Ce
ℓ (cm)	3.60	3.20	2.40	2.30	2.10
gap (cm)	0.30	0.27	0.20	0.19	0.18
N° cristalli	$20 \times 20 \times 20$	$22 \times 22 \times 22$	$28 \times 28 \times 28$	$27 \times 27 \times 27$	$30 \times 30 \times 30$
L (cm)	78.00	76.34	72.80	67.23	68.40
λ_I totali (λ_I)	1.80	2.31	3.09	2.72	3.01
X_0 totali (X_0)	38.88	34.73	24.96	55.54	53.75
G $(m^2 sr)$	9.56	9.15	8.32	7.10	7.35

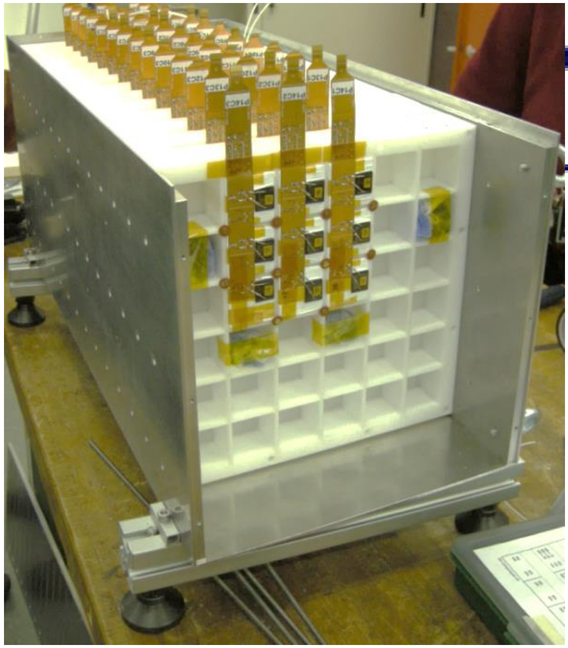
- **Cube of cubes, 1 Moliere-radius size each**
- **Total weight ~2 tons**
- **Active-volume fraction 78%**



Best choice dictated by balance between size (**density of the absorber**) and shower-containment (**interaction length**), which determine energy resolution

All the five geometries satisfy the basic requirements by providing an effective geometrical factor of at least 2.5 m^2sr with an energy resolution better than 40%.

Prototype v1



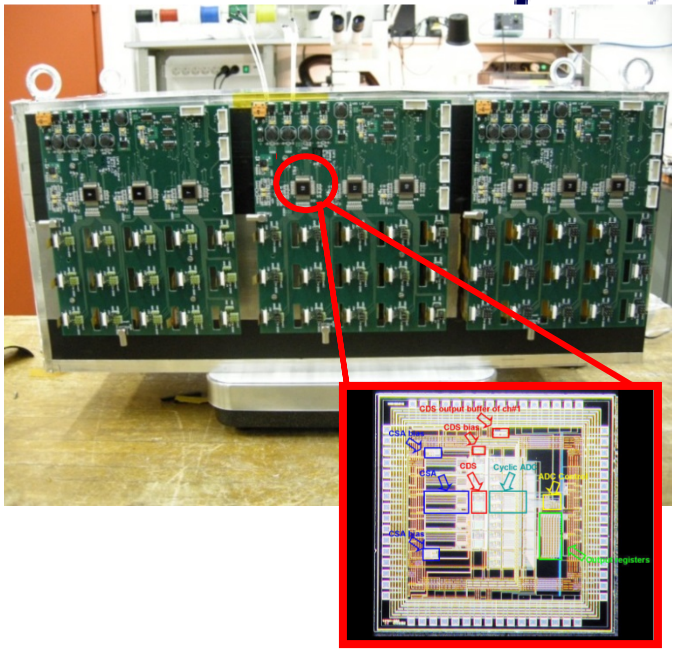
- **15 Layers**
- **3 x 3 CsI(Tl) crystals in each layer**
- Crystal side ~ Moliere radius (3.6 cm)
  - ~ **1.5 R_M** shower containment
- Gap 0.4 cm
- A big PD (VTH2090, 84.64 mm^2) for each crystal
- A small PD (VTH9412, 1.6 mm^2) for 3 crystals
- **Depth for vertical track:**
  - active depth **28.4 X_0 → 1.35 λ_I**
- Wrapping materials:
  - Version 1.0: Teflon
  - Version 1.2: Vikuiti
- 3 front-end electronics board:
  - 9 CASIS chip, 3 ADC

Three upgrades (v1.0-1-2), tested with particle beams

Feb 2013	v1.0	Ions Pb+Be 13-30 GeV/u
Mar 2015	v1.1	Ions Ar+Poly 19-30 GeV/u
Aug/Sep 2015	v1.2	μ, π,e 50-75-150-180 GeV

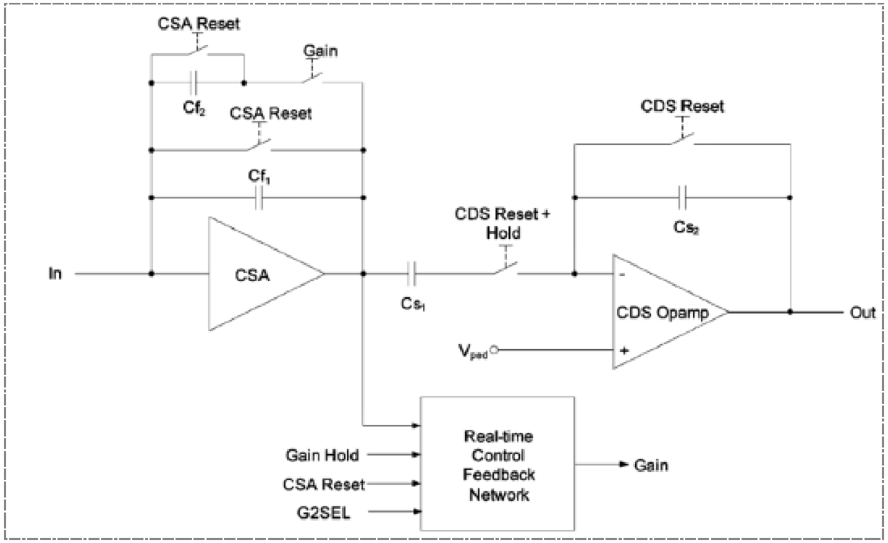
Front-end electronics

- **ASIC chip CASIS (HIDRA) developed by INFN Trieste**
- 16 (28) channels
- Charge Sensitive Amplifier
- Double-gain 1:20 with an automatic gain-selection circuitry
- Correlated Double Sampling (CDS) filter.

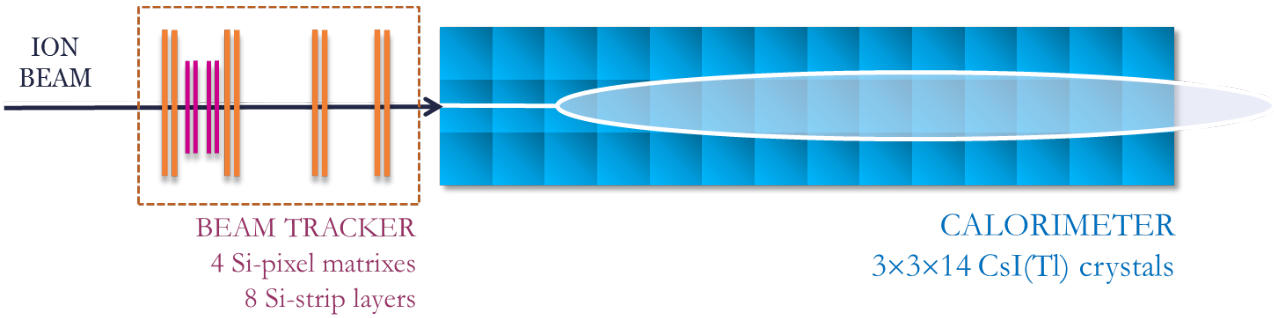


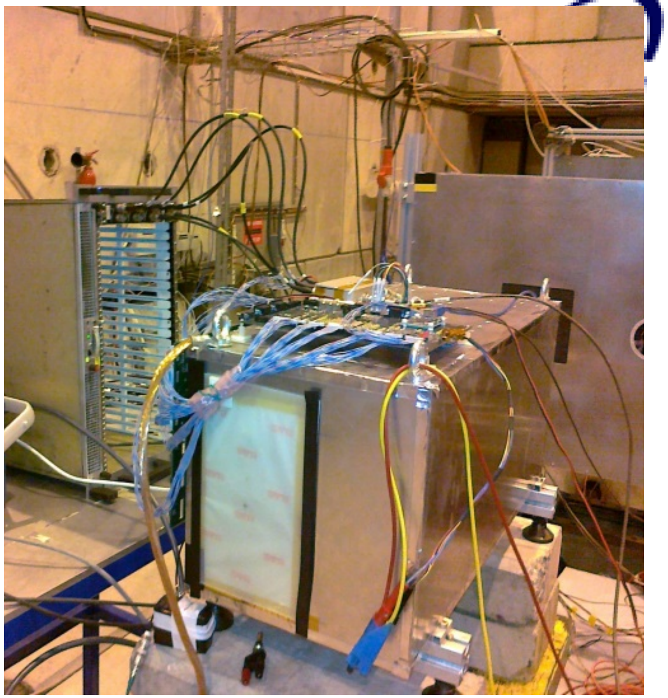
PERFORMANCE

- High dynamic: from ~fC to 52.6 pC
- Low noise (ENC ~ $2280e^{-} + 7.6e^{-}/pF$)
- Low power consumption: 2.8 mW/channel



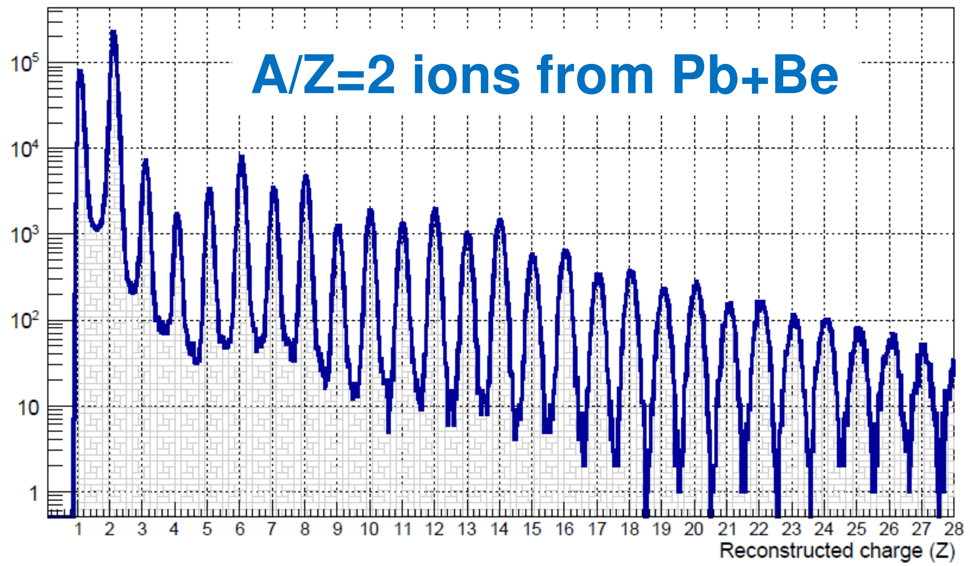
Test with ion-beam

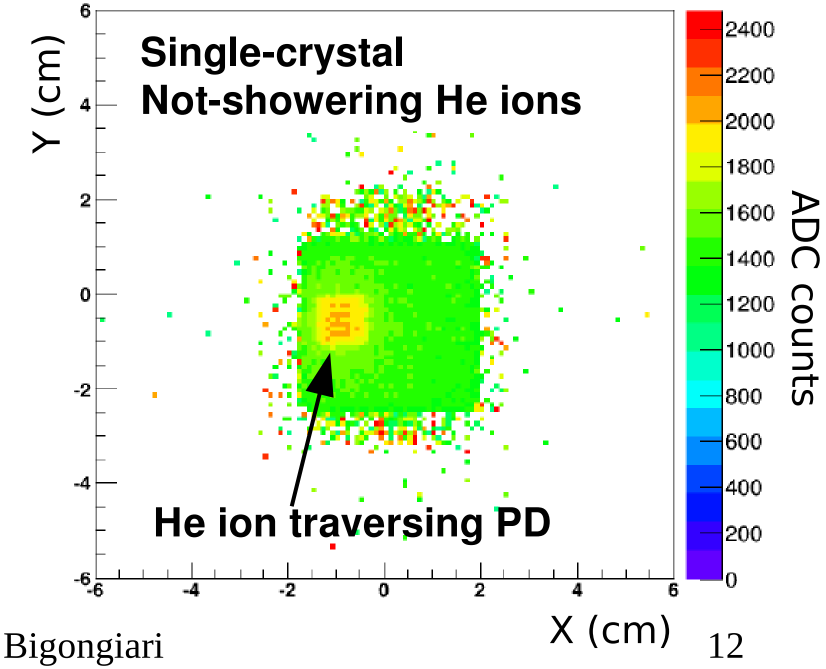




Prototype v1.0 exposed to ion beams of 13 and 30 GeV/n (Feb-2013 @CERN-SPS)

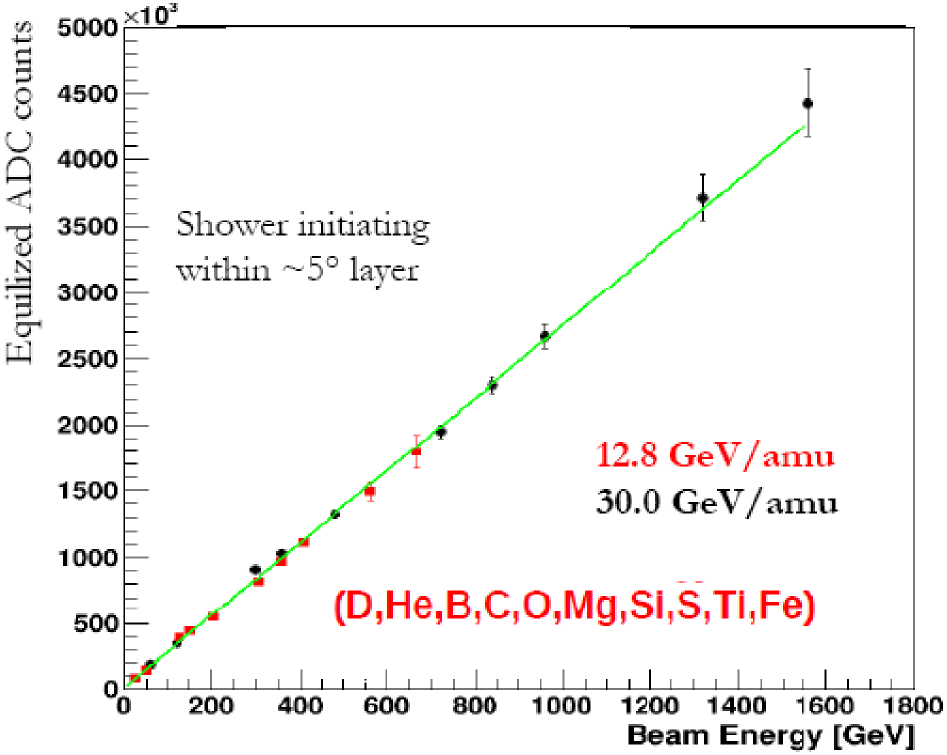
Precise Z-tagging & beam position from BT (INFN Pisa/Siena)





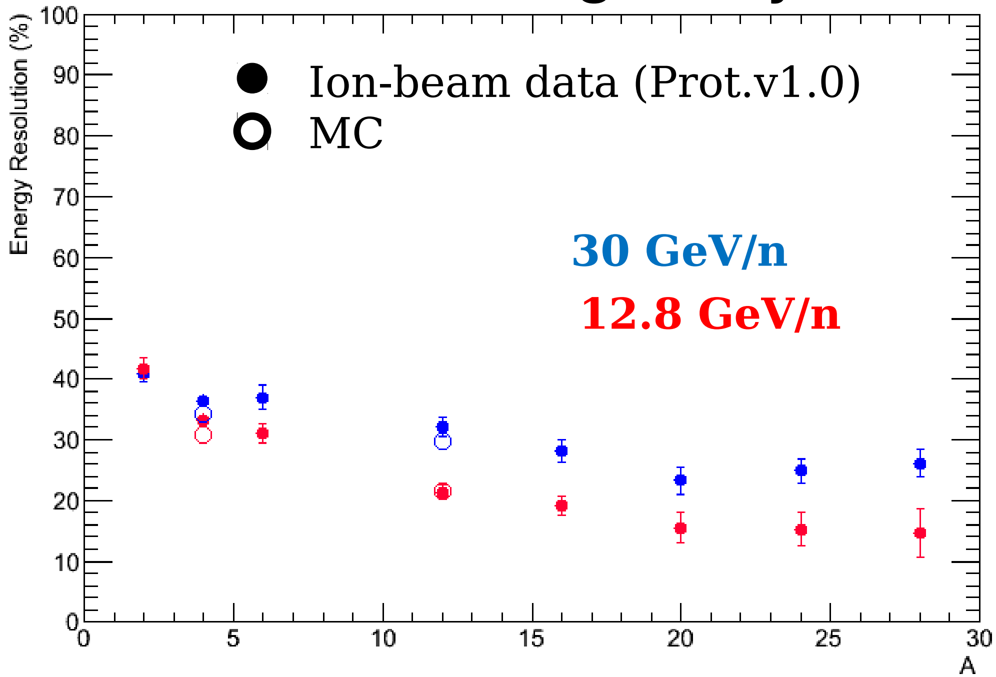
Linearity vs beam energy

Good linearity up to 1.6 TeV of ion energy with just the large area photodiode



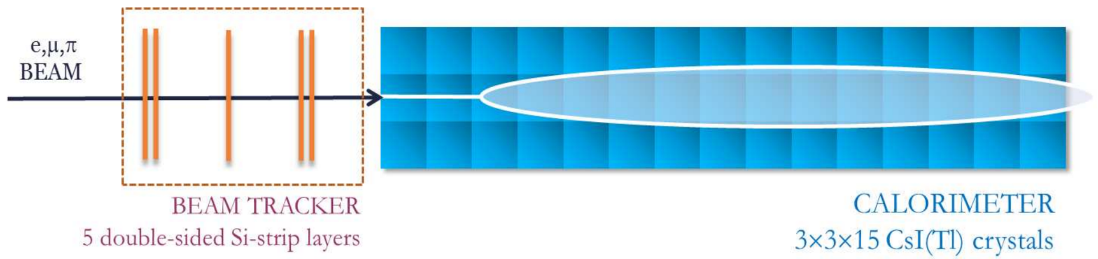
Energy resolution improves with A. Good agreement between data and MC

Showers starting on layer 3

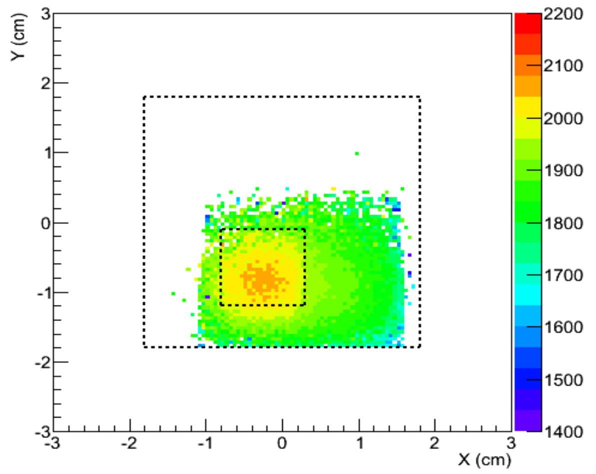


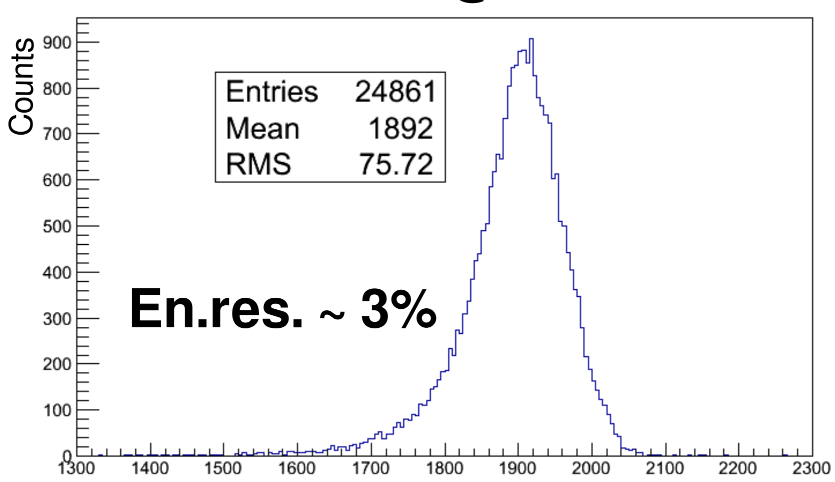
Beam test with electrons

- CERN, SPS, H8 area, Electron from 50 GeV to 200 GeV



- Electrons @ 50 GeV: the PD direct ionization has big impact on the energy deposit (and energy resolution) because all tracks are vertical



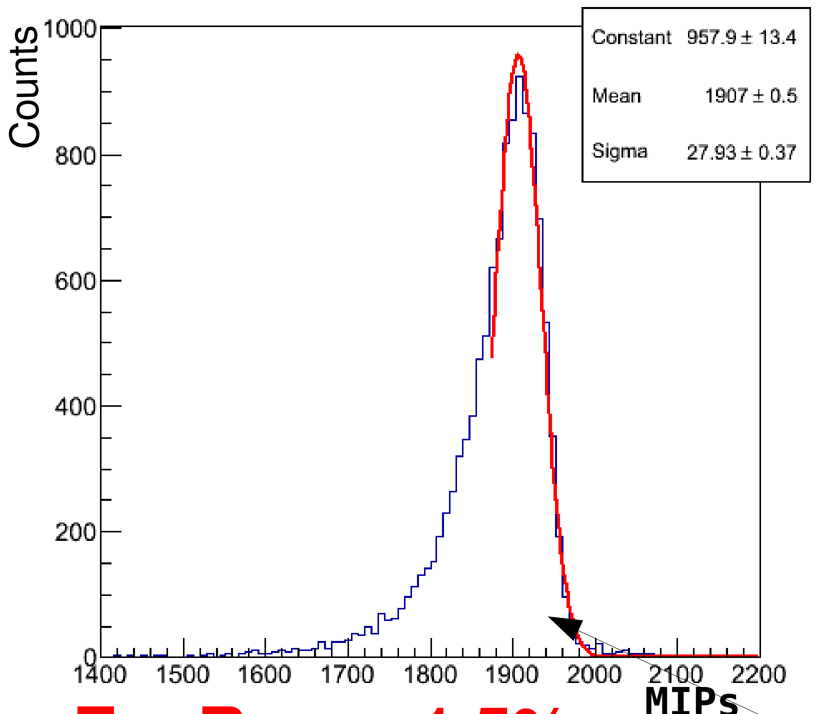


- In order to study the prototype performance a FLUKA based simulation with detailed prototype geometry was developed

Mc data vs beam data

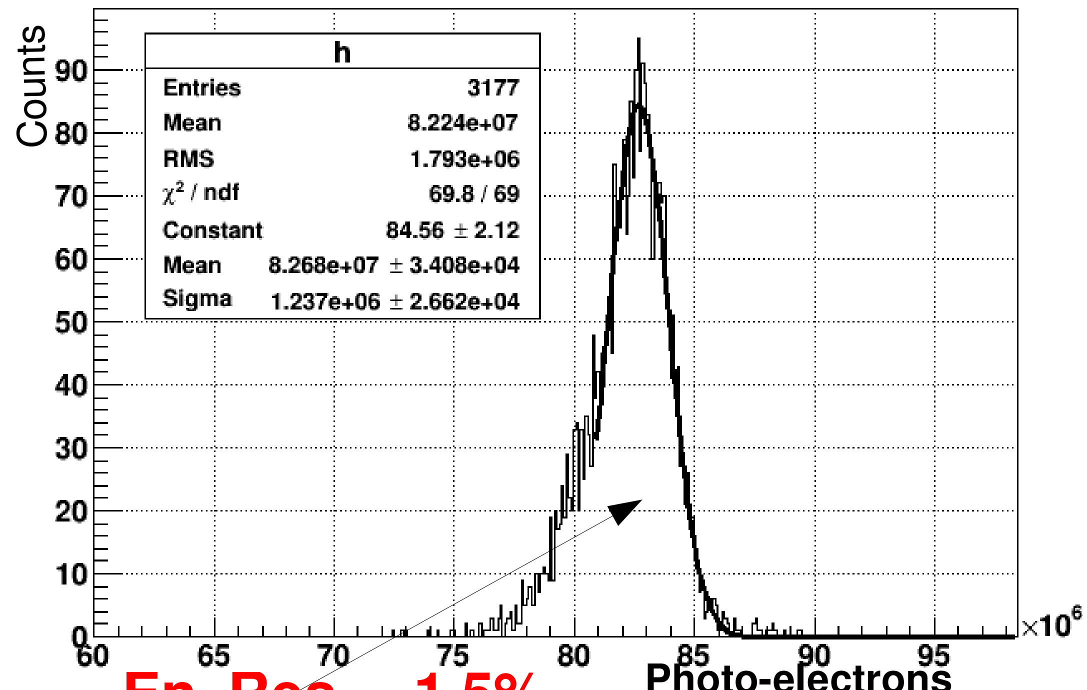
- Electrons @ 50 GeV energy deposit after <u>geometrical selection of events with direction that does not intercept the PD</u> (both in simulation and beam data)

Beam data: Electron @ 50 GeV



En. Res. ~ 1.5%

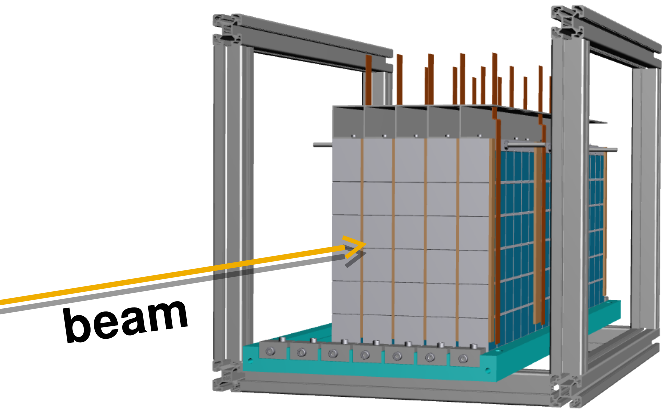
MC data: Electron @ 50 GeV



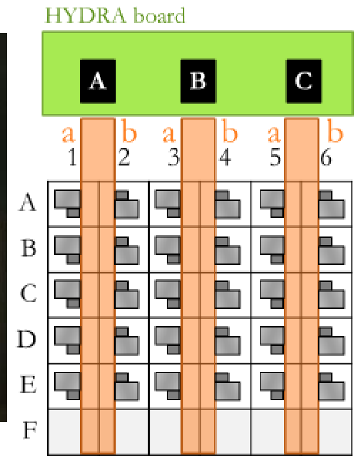
En. Res. ~ 1.5%

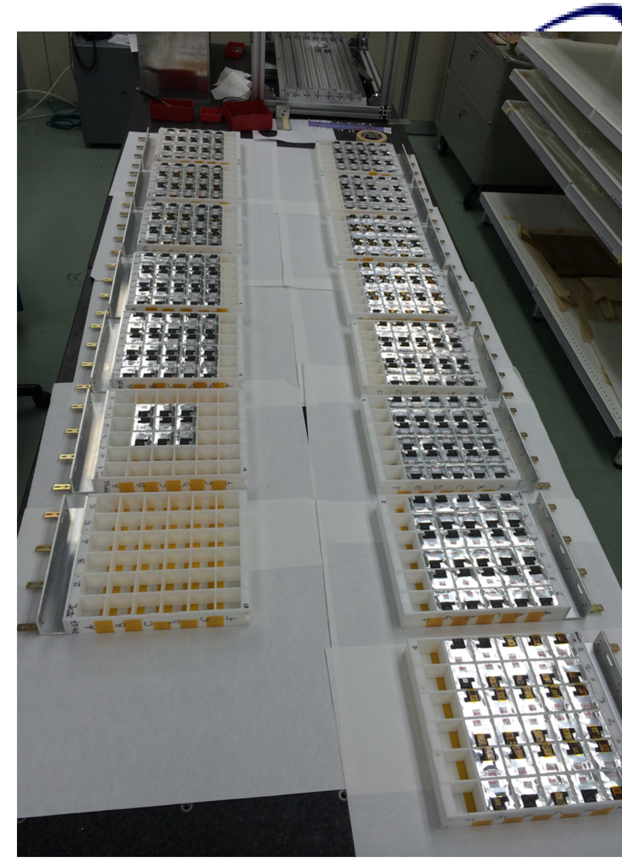
- **Very good agreement between simulation and beam data**

Prototype upgrade (v2.0)



● Mechanics: INFN Pisa





- **Prototype mechanics completely redesigned**
  - **18 trays x 25 crystals each**
  - **trays mounted sideways!**
- 18 layers along the beam line
  - active depth **35.0 X_0 → 1.6 I_I**
- 5x5 elements for each layer
- PDs placed laterally

- **First version of HYDRA chip (28 channels)**
- **Two-PD readout**
- **5x5x18 instrumented elements**
- **Tested with particle beam at CERN SPS:**

Sep 2016	**v2.0**	**μ,π,e 50->200 GeV**

- **Data analysis: INFN Florence+Pisa, CIEMAT Madrid**

Conclusion

- The CaloCube R&D project, aiming to develop a novel design calorimeter, optimized for high-energy CR measurements in space, was presented.
- As a proof-test of the CaloCube concept, a prototype made of CsI(Tl) and readout by PDs has been constructed and tested, in several versions, with particle beams.
  - Analysis under progress
  - Present results (3x3x15 detector matrix):
    - Better than 40% energy resolution for ions up to 30 GeV/n
    - Better than 1.5% energy resolution for electrons up to 200 GeV
    - Two-sensor readout tested (even if with reduced dynamic): small-PD performances comparable with large-PD ones @200 GeV
  - Next beam test @SPS in August 2017
    - Optimized optical coupling

Thank You

Spare slides

Geometry & Materials

- **Optimization of energy resolution and acceptance for protons**
- **Same simulations and analysis with different materials and distance among crystals (gap)**

- **Cube of cubes, 1 Moliere-radius size each**
- **Total weight ~2 tons**
- **Active-volume fraction 78%**

	CsI:Tl	BaF_2	YAP:Yb	BGO	LYSO:Ce
ℓ (cm)	3.60	3.20	2.40	2.30	2.10
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N° cristalli	$20 \times 20 \times 20$	$22 \times 22 \times 22$	$28 \times 28 \times 28$	$27 \times 27 \times 27$	$30 \times 30 \times 30$
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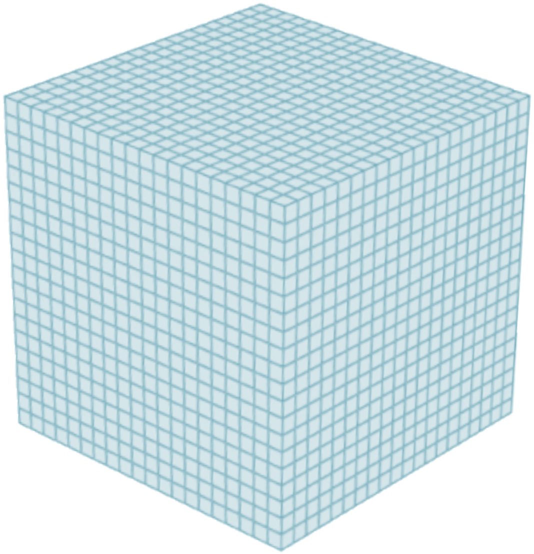
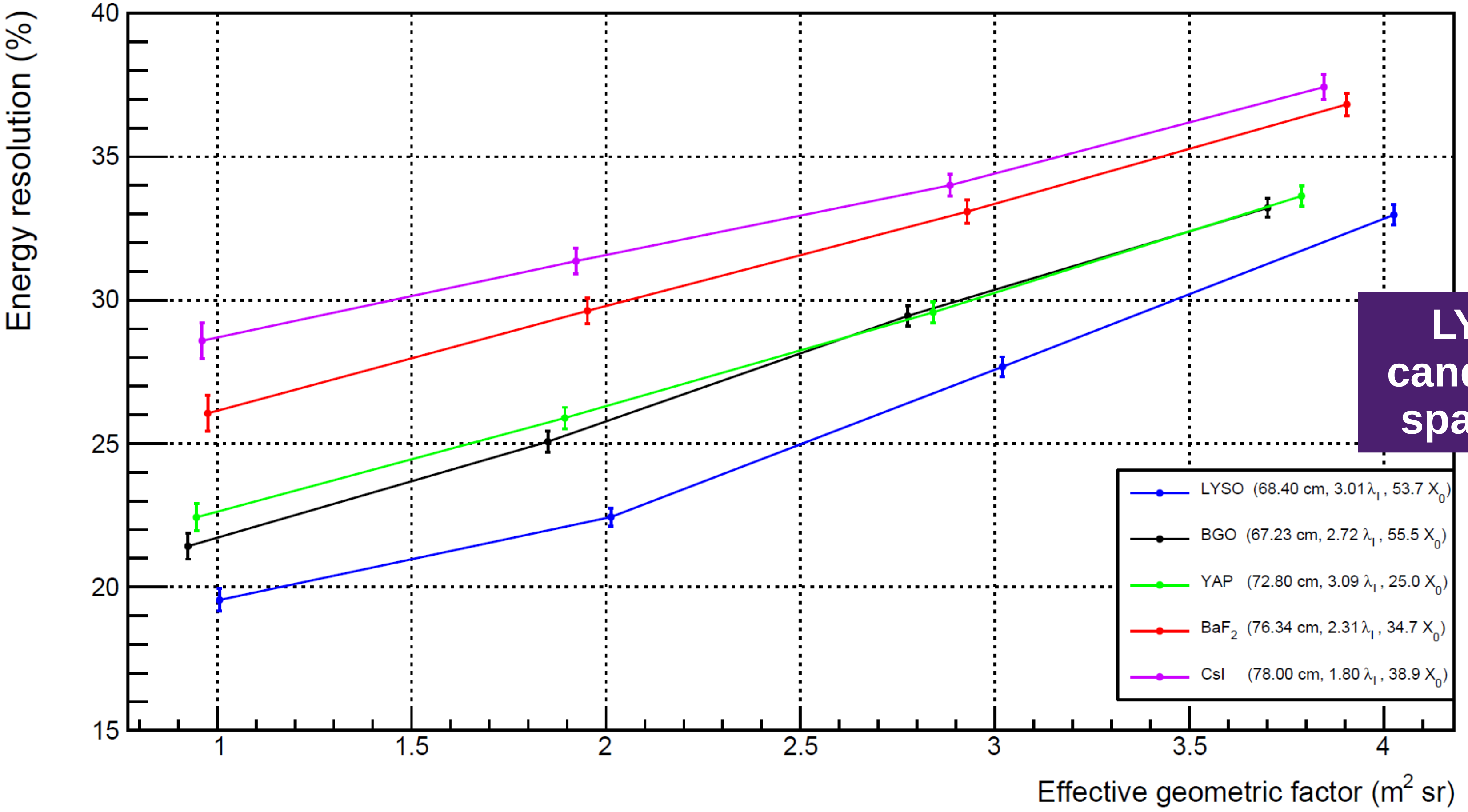


Best choice dictated by balance between **size** (density of the absorber) and **shower-containment** (interaction length), which determine energy resolution

Materials: energy resolution vs acceptance

- **Proton @ 1TeV**
- **Effective geometric factor = $GF_{single\_face} * 5 * \varepsilon_{Selection}$**

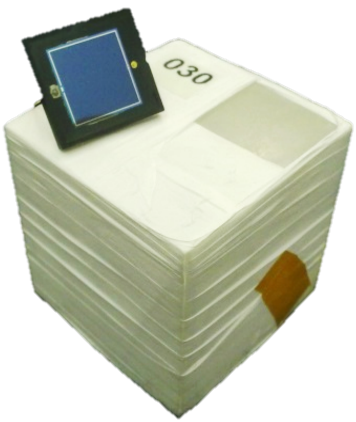


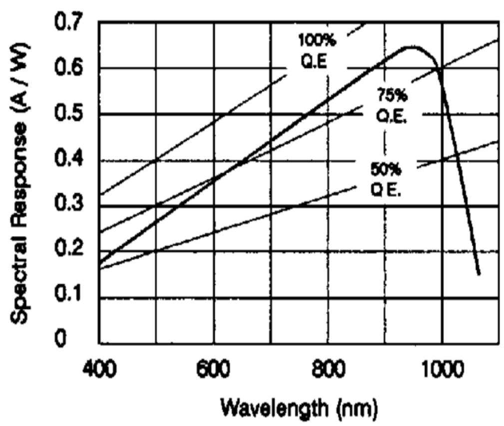
LYSO is a good candidate for future space calorimeters

Sensors

Large area photodiode VTH2090:

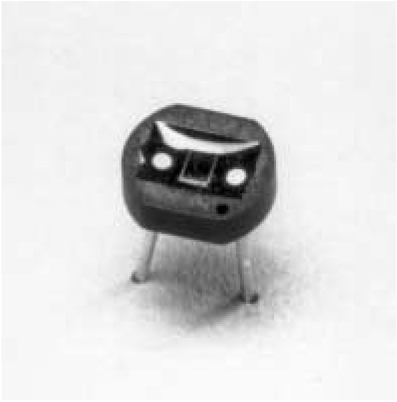
- Active area 84.64 mm^2
- 1 MIP in CsI(Tl) ~ 7fC
- Max signal 30 nC (>> CASIS range)

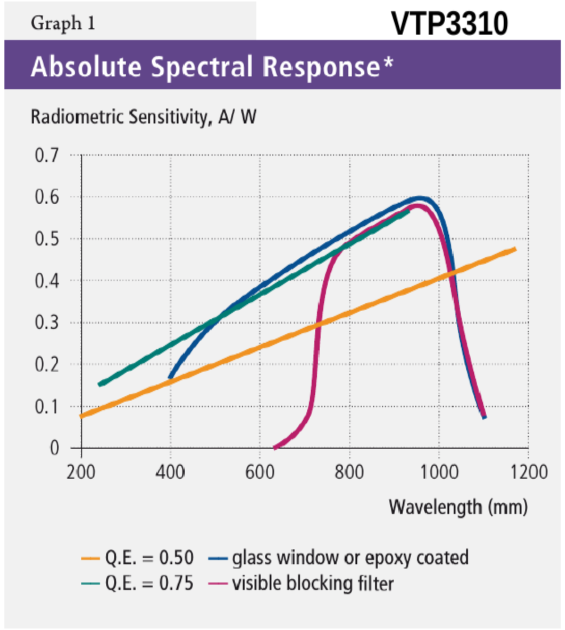




Small area photodiode VTH9412:

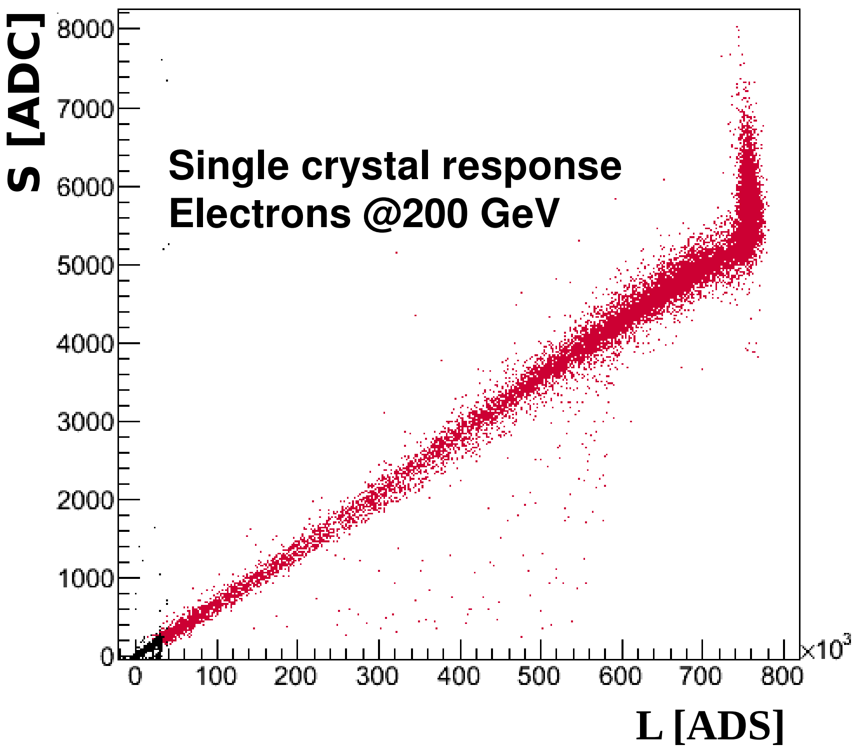
- Active area 1.6 mm^2
- Max signal 300 pC (> CASIS range)

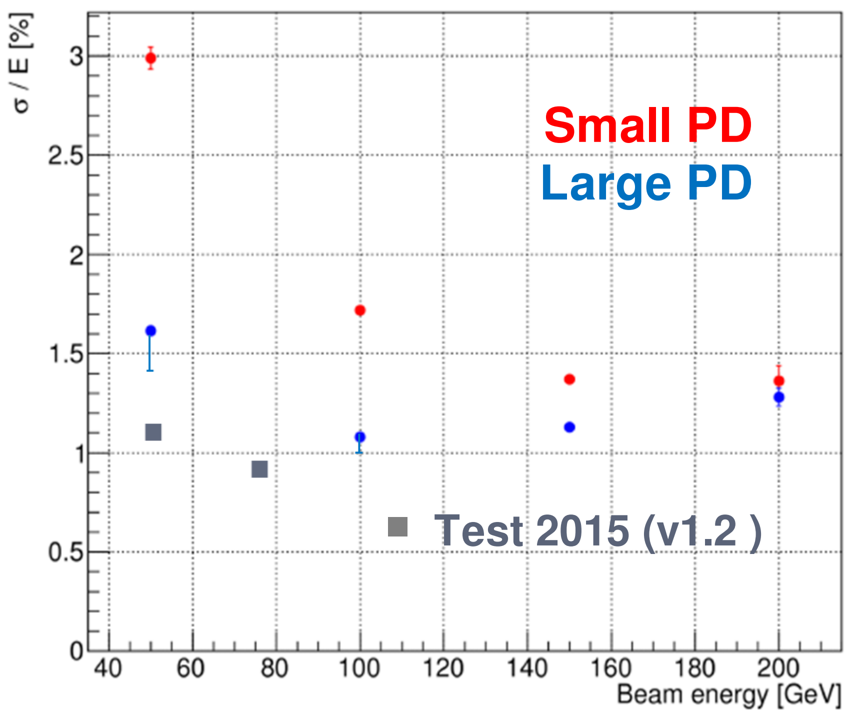




Energy resolution – e.m. showers

- Signal induced by MIPs used to equalize crystal responses
  - v2.0 setup: noise ~ 60↔80 ADC ⇒ $<S/N>_{1MIP} \lesssim 10$
- Signal induced by showers used to equalize relative sensor responses R=L/S





Energy resolution for e.m. showers:

- Better than 1.5% up to 200 GeV with Large PDs
- Comparable performances with Small PD above 200 GeV